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EXPERIMENT AND THEORY ON THE FORBUSH DECREASE IN COSMIC RAY ACTIVITY

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ABSTRACT. The free exchange of particles behind a "semi-transparent" magnetic piston is assumed to be a feature of Forbush decrease in this evaluation of possible changes in the properties of the piston as the result of solar emission and a reduction of its velocity.

1. Statement of the Problem

In its time, the study of Forbush decreases of cosmic rays has played an important role in the understanding of dynamic processes in interplanetary space. Indeed, until the beginning of the IGY it was the sole method of studying electromagnetic conditions in interplanetary space during periods of disturbances. In particular, it was possible in those days to determine on the basis of observations of cosmic rays that the corpuscular flows that create powerful magnetic storms have regular inhomogeneities, and that the field intensity in them must reach several tens of gamma [1]. /1890*

The rapid development of experimentation in the last 10 years (use of special spacecraft and earth and lunar satellites for investigations, construction of a world-wide network of neutron monitors, a sharp increase in the accuracy of recording with meson monitors on the surface of the Earth and at various depth below ground) has made it possible to obtain much more complete information on the nature of the change in intensity of cosmic rays. The following have been observed: nonuniformity of the beginning of Forbush decreases; a significant change in the decrease spectrum from one storm to the next and during the process of a Forbush decrease; the important effect of magnetic storms on the anisotropy of cosmic rays (for a survey of work up to 1963, see [2]; after 1963, [3].

How has the theory of Forbush decreases developed in recent years? It must be admitted that the situation here is much worse than in the field of experiment. As a matter of fact, the principal efforts in the theory of

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*Numbers in the margin indicate pagination in the foreign text.

modulation of cosmic rays have been directed toward the development of the convection-diffusion model of Parker [4] in the approximations of an equation of anisotropic diffusion [5-9] and a kinetic equation [10-12]. However, it has been possible to obtain concrete solutions only for the simplest stationary cases with assumption of spherical symmetry.

The effect of a regular magnetic field on cosmic rays was discussed in [1] while [2] dealt with a model of a "semitransparent" magnetic piston. It seems to us that a model of a "semitransparent" magnetic piston is a basically correct description of the physics of Forbush decreases, but that the detailing and gradual complication of this model are unnecessary for an understanding of the many new experimental results. In particular, [2] and [13] considered a model of a "semitransparent" magnetic piston in which it was assumed that an exchange of particles in the radial direction behind the piston does not occur, but that there is diffusion only in the transverse direction, so that the intensity of the cosmic rays following a Forbush decrease rises exponentially. However, since the magnetic field behind the piston has a basically radial nature, the assumption of a free exchange of particles behind the piston in the radial direction is, indeed, close to reality. We will also consider this case here. In addition, we shall also /1891
make an effort to evaluate the possible change in the properties of the magnetic piston as a measure of emission from the Sun and reduction of its velocity.

2. Case Where There is Free Exchange by Particles Behind A "Semitransparent Magnetic Piston

The geometry of the model and the designations used for this case are shown in the figure. Let n_1 represent the reduction of the density of cosmic rays on the axis of the region; then in the first approximation the distribution of cosmic rays in the transverse direction will be

$$n(r,\rho)=n_1+\frac{n_0-n_1}{r\,\mathrm{tg}\,\psi}\cdot\rho, \qquad (1)$$

and the total number of particles in the volume behind the piston will be

$$N=\int_0^{r_0} dr \int_0^{r\,\mathrm{tg}\,\psi} n(r,\rho)2\pi\rho\, d\rho = \tag{2}$$
$$=\frac{2\pi}{9} r_0^3 (n_1+2n_0)\,\mathrm{tg}^2\,\psi.$$

The balance equation for the particles is then

$$\frac{dN}{dt}=I_1+I_t \tag{3}$$

where I_1 is the total flux of particles through the lateral surface and I_t is the total flux through the piston. From (2) it follows that

$$\frac{dN}{dt}=\frac{2\pi}{3} r_0^2 (n_1+2n_0)\,\mathrm{tg}^2\,\psi u+\frac{2\pi}{9} r_0^3\,\mathrm{tg}^2\,\psi \frac{dn_1}{dt}, \tag{4}$$

where it is considered that $dr_0/dt = u$. Now we find

$$I_б=\int_0^{r_0} \frac{2\pi r\,\mathrm{tg}\,\psi}{2} \varkappa_2\, \mathrm{grad}\, n\, \mathrm{dr} \approx \int_0^{r_0} \pi r\,\mathrm{tg}\,\psi \varkappa_2 \frac{n_0-n_1}{r\,\mathrm{tg}\,\psi} dr=\pi(n_0-n_1) r_0 \varkappa_2. \tag{5}$$

Noting (1), we then find

$$I_п \approx \int_0^{r_0\,\mathrm{tg}\,\psi} \frac{n_0-\left(n_1+\frac{n_0-n_1}{r_0\,\mathrm{tg}\,\psi}\rho\right)}{L} \varkappa_1 2\pi\rho\, d\rho=\frac{\pi}{3L}(n_0-n_1)\varkappa_1 r_0^2\,\mathrm{tg}^2\,\psi. \tag{6}$$

Substituting (4-6) into (3) and considering $udt = dr_0$, we will have

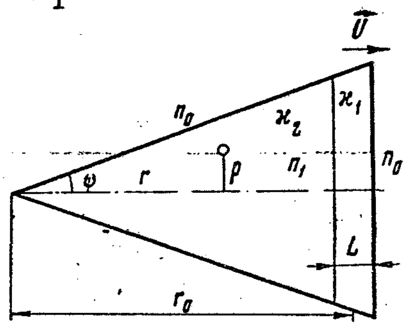
$$\frac{dn_1}{dr_0}=-n_1\left[\frac{9\varkappa_2}{2ur_0^2\,\mathrm{tg}^2\,\psi}+\frac{3\varkappa_1}{2Lur_0}+\frac{3}{r_0}\right]+ \tag{7}$$
$$+n_0\left[\frac{9\varkappa_2}{2ur_0^2\,\mathrm{tg}^2\,\psi}+\frac{3\varkappa_1}{2Lur_0}-\frac{6}{r_0}\right].$$

The solutions of (7) are written in the form /1892

$$n_1(r_0) = \exp\left[-\int_{r_1}^{r_0}\left(\frac{9\varkappa_2}{2u\zeta^2\,\mathrm{tg}^2\,\Psi}+\frac{3\varkappa_1}{2Lu\zeta}+\frac{3}{\zeta}\right)d\zeta\right]\left\{n_0\int_{r_1}^{r_0}\left[\frac{9\varkappa_2}{2u\zeta^2\,\mathrm{tg}^2\,\Psi}+\right.\right.$$

$$\left.\left.+\frac{3\varkappa_1}{2Lu\zeta}-\frac{6}{\zeta}\right]\exp\left[\int_{r_1}^{\zeta}\left(\frac{9\varkappa_2}{2u\chi^2\,\mathrm{tg}^2\,\Psi}+\frac{3\varkappa_1}{2Lu\chi}+\frac{3}{\chi}\right)d\chi\right]d\zeta+n_1(r_1)\right\}, \tag{8}$$

where $n_1(r_1)$ is the initial condition for the density behind the piston at $r_0 = r_1$.



Geometry of the Model and Designations Used.

Generally speaking, the nature of the relationship $n_1(r_0)$ is determined to a significant degree by the relationship of L, u, κ_1 and κ_2 on r_0.

Let us begin by assuming that

$$u = \mathrm{const};\ \varkappa_2 = \varkappa_{2\text{б}}\left(\frac{r_0}{r_{\text{б}}}\right);\quad \frac{\varkappa_1}{L} = \mathrm{const}. \tag{9}$$

Then (8) is written in the form

$$n_1(r_0) = n_0\left[1-\left(\frac{r_1}{r_0}\right)^{\frac{9\varkappa_{2\text{б}}}{2ur_{\text{б}}\,\mathrm{tg}^2\,\Psi}+\frac{3\varkappa_1}{2Lu}+3}\right]\frac{\dfrac{3\varkappa_{2\text{б}}}{2ur_{\text{б}}\,\mathrm{tg}^2\,\Psi}+\dfrac{\varkappa_1}{2Lu}-2}{\dfrac{3\varkappa_{2\text{б}}}{2ur_{\text{б}}\,\mathrm{tg}^2\,\Psi}+\dfrac{\varkappa_1}{2Lu}+1}+$$

$$+n_1(r_1)\left(\frac{r_1}{r_0}\right)^{\frac{9\varkappa_{2\text{б}}}{2ur_{\text{б}}\,\mathrm{tg}^2\,\Psi}+\frac{3\varkappa_1}{2Lu}+3} \tag{10}$$

It follows from (10) that at $r_0 \gg r_1$, $n_1(r_0)$ approaches the asymptotic stationary value

$$n_1(r_0) = n_0\left[1-\frac{4Lur_{\text{б}}\,\mathrm{tg}^2\,\psi}{L\varkappa_{2\text{б}}+r_{\text{б}}\varkappa_1\,\mathrm{tg}^2\,\psi}\right]\left[1+\frac{2Lu\,r_{\text{б}}\,\mathrm{tg}^2\,\Psi}{L\varkappa_{2\text{б}}+r_{\text{б}}\varkappa_1\,\mathrm{tg}^2\,\Psi}\right]^{-1}. \tag{11}$$

The expected $n_1(r_0)/n_0$ as functions of L, u, $\kappa_{2\text{б}}$, κ_1, and tg Ψ are listed in Table 1.

TABLE 1

Expected Relative Forbush-Decrease $n_1 - n_0/n_0$ (In Percent) According to [11] for Various Values of Dimensionless Parameters

a	b									
	0.001	0.003	0.01	0.03	0.1	0.3	1	3	10	30
0.001	0.300	0.299	0.297	0.291	0.273	0.230	0.150	0.075	0.030	0.010
0.003	0.895	0.894	0.888	0.870	0.815	0.690	0.450	0.225	0.082	0.029
0.01	2.97	2.96	2.94	2.89	2.70	2.29	1.49	0.75	0.273	0.097
0.03	8.72	8.70	8.65	8.50	7.96	6.77	4.43	2.23	0.815	0.29
0.1	27.2	27.2	27.0	26.5	25.0	21.4	14.3	7.33	2.70	0.97
0.3	69.1	69.1	68.7	67.6	64.3	56.3	39.1	20.9	7.96	2.87

It is apparent from Table 1 that when the factor

$2Lu/\kappa_1$ is critical. For large Forbush decreases with an smplitude greater than 10% the value $2Lu/\kappa_1 \gtrsim 0.03$. This means that at $L \approx 10^{12}$ cm, $u \approx 10^8$ cm$\cdot$sec^{-1} /1893
(the assumed value of L corresponds to a time of rapid fall of about 3 hours), the value of $\kappa_1 \lesssim 6\cdot 10^{21}$. For relativistic particles, this gives a transport path for scattering $\Lambda \lesssim 6\cdot 10^{11}$ cm. The value found for Λ is not excessively small, since according to the data on the flare of solar cosmic rays on 28 September 1961, under undisturbed conditions in interplanetary space for particles with an energy $\lesssim$ 600 MeV, $\Lambda \approx 8\cdot 10^{11}$ cm. Therefore, in the piston, which is essentially a shock wave with a plasma and magnetic field that have been compressed several times, we can expect that for particles with an energy of ~10 BeV the value of the transport path for scattering completely can assume a value of $\lesssim 6\cdot 10^{11}$ cm. Then the intensity of the magnetic field in the shock wave must be

$$H \gtrsim \frac{10^{10}}{300\cdot 6\cdot 10^{11}} = 5\cdot 10^{-5} \quad (12)$$

which is known to be the case. For a number of powerful magnetic storms the modulations undergone by particles with an energy of ~30 BeV [2] in these cases must be $H \gtrsim 1.5 \cdot 10^{-4}$ G.

3. Profiles of Forbush Decrease in a Model of a "Semitransparent" Magnetic Piston

If free exchange by particles in the radial direction does not occur behind the piston, the following profiles will exist when the Earth is enclosed by the piston:

a) Type I profile, with a sharp decrease of the intensity of cosmic rays and a gradual rise according to exponential law in the case where the piston is more or less uniform over its entire structure;

b) Type II profile, with a sharp decrease of intensity immediately following enclosure of the Earth by the piston, then with a smoother decline (upon passage into a part of the piston with a greater value of κ_1) and finally with a smooth rise exponentially in the case where the piston is characterized by a lower value of κ_1 than the posterior part);

c) Type III profile, with a gradual decline of the intensity of cosmic rays to a minimal value and a gradual rise in the case of enclosure of the Earth in the lateral surface of a modulating volume.

However, if there is a free exchange of particles in the volume behind the piston, the type of profile of Forbush decrease is determined completely by the dynamics of the piston and the nature of the transverse diffusion behind the piston. As the Earth penetrates deeper into the depths of the magnetic piston, the density of the cosmic rays declines from n_0 to $n_1(r_0)$. In the first approximation, this drop will be linear, but a more detailed picture will be determined by the magnetic structure of the piston. In particular, during the period of rapid decline (i.e., as the Earth penetrates the depths of the piston) it is possible to have fluctuations of intensity and the appearance of significant anisotropy.

If, at the moment that the Earth is overtaken by the piston, the intensity of cosmic rays in the volume behind the piston has a tendency to decrease (which in turn is determined by the behavior of parameters L, u, κ_1, κ_2 and r_0

in (10) and (11)) it begins to rise again. Hence, in this case there will be a Type II profile. It may also happen that at the moment the Earth is over- /1894 taken by the piston there is a tendency for a rise in the intensity of cosmic rays behind the piston. Then, as we can easily see, there will be a Forbush decrease with a Tupe I profile.

4. Perspectives for the Further Development of the Theory of Forbush Decrease

A model of a "semitransparent" magnetic piston in the approximations considered here and in [2, 4, 13] makes it possible to understand only the basic outline of a Forbush decrease, a sharp drop in intensity with a subsequent gradual rise. As far as such important aspects of a Forbush decrease as the anisotropic nature of the drop in intensity (nonuniformity of the beginning at various stages with different asymptotic cones of particle reception) are concerned, the presence of significant fluctuations in the period of rapid decline of intensity, excitation of the first and second harmonics of solar-daily variation in the period of a Forbush decrease, the appearance of an extra-terrestrial source of increased intensity of cosmic rays in the period of the main phase of a magnetic storm (except the source of an increase that is linked to the processes in the magnetosphere of the Earth), this model of a "semitransparent" magnetic piston within the framework of the considered approximations cannot explain them qualitatively and surely not quantitatively. For this we must keep in mind, in addition to nonuniformity of the magnetic field, the presence of a regular field, i.e., the problem of the motion of the piston in the gas of the cosmic rays must be solved within the framework of an approximation of anisotropic diffusion [6-9], or, more exactly, within the framework of a kinetic equation [10-12] (all the more so, since it follows from the estimates made in Section 2 above that the transport path for scattering of the particles is comparable with the thickness of the piston L). However, in such a statement, the problem of a moving piston with boundary conditions on a moving boundary is rather complex, but its solution for several comparatively simple assumptions can obviously be obtained with the aid of a computer.

It seems to us that such a problem is deserving of considerable attention, since its solution will make possible the intense utilization of an enormous volume of experimental data on Forbush decreases of cosmic rays to obtain valuable information on electromagnetic conditions in interplanetary space in excited periods and on dynamic processes caused by shock waves in the solar wind.

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